SMALL-SCALE HIGH PERFORMANCE MAGAZINE ROOF AND SOIL COVER FEASIBILITY TEST RESULTS

by

Robert N. Murtha

Structures Division
Naval Civil Engineering Laboratory
Port Hueneme, California

ABSTRACT

The High Performance (HP) Magazine concept consists of an earth-covered box structure with interior cells where munitions are stored. The cells are designed to prevent sympathetic detonation between cells, thereby limiting the Maximum Credible Event (MCE) to the Net Explosive Weight (NEW) stored in any cell. The reinforced concrete box structure and soil cover are designed to limit the safe distance for the MCE from blast, fragment, and debris outside the magazine.

Small-scale (1/10) feasibility tests were conducted by the Terminal Effects Research & Analysis (TERA) Group at Socorro, NM in 1991. Results from these tests will be used to demonstrate the feasibility of the HP Magazine roof and soil cover to mitigate external debris and pressure hazards. A reusable magazine test fixture was built and six tests were performed in which 2.4 in. thick reinforced concrete roof specimens were covered with 0, 3.6, and 7.2 in. of soil. The explosive test charges were 7.43-lb rectangular blocks of Composition C4 (equivalent to 10 lb of TNT). Data included airblast instrumentation, high-speed motion pictures, and debris recovery.

The test results demonstrated the feasibility of the HP Magazine roof and soil cover to mitigate external debris and pressure hazards. For a full-scale 10,000-lb MCE, the safe ESQD (Explosive Safety Quantity Distance) pressure arc was reduced to about 500 ft (23.2 $W^{1/3}$), the distance from the magazine that the peak pressure decays to 1.2 psi. The full-scale ESQD arcs for debris were reduced to about 800 ft (37.1 $W^{1/3}$) and 550 ft (25.5 $W^{1/3}$) for soil covers of 3 and 6 ft, respectively. This is much less than the NAVSEA OP-5 (Reference 1) ESQD arc for debris and fragment which is 1,250 ft.

INTRODUCTION

Background

A new storage magazine is needed by the Navy to solve munitions storage problems. Existing magazines encumber large land areas to meet ESQD requirements of NAVSEA OP-5. NCEL is currently investigating the feasibility of a new magazine (Reference 2) that will reduce the land area encumbered by ESQD arcs and improve the efficiency of weapons handling operations. This new HP Magazine concept would reduce

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1992**	2. REPORT TYPE	3. DATES COVERED **00-00-1992 to 00-00-1992**

4. TITLE AND SUBTITLE **Small-Scale High Performance Magazine Roof and Soil Cover Feasibility Test Results**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Civil Engineering Laboratory,Structures Division,Port Hueneme,CA,93041**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA260984, Volume I. Minutes of the Twenty-Fifth Explosives Safety Seminar Held in Anaheim, CA on 18-20 August 1992.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**41**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

encumbered land by 80% (or increase storage density on existing land by a factor of up to 8 times) and significantly reduce operational costs. Reduction of encumbered land is achieved by reducing the Maximum Credible Event (MCE) in the magazine to 10,000 lb Net Explosive Weight (NEW) of High Explosive (HE) by using cells with walls that prevent sympathetic detonation (SD). The magazine would be designed to store about 200,000 lb (NEW) of palletized ordnance (e.g., bombs, bullets, projectiles, torpedoes) or about 60,000 lb of containerized missiles. However the ESQD arcs would be based on an MCE of only 10,000 lb (the NEW in one cell).

The safe ESQDs are given in Reference 1. The pressure ESQD arc for an MCE of 10,000 lb is 862 ft ($40W^{1/3}$, the distance from the magazine that the peak pressure decays to 1.2 psi). This is much less than the OP-5 ESQD arc for debris and fragments which is 1250 ft (the distance at which the hazardous debris density is 1 per 600 ft^2). The debris and fragment safe distance must be reduced in order to take full advantage of the low MCE.

The HP Magazine concept includes a reinforced concrete roof and added soil cover to mitigate the fragment and debris hazard. The roof and soil cover will stop high velocity primary weapon fragments. The reinforced concrete roof will use close flexural steel spacing and shear stirrups to reduce the area of breaching. Deeper than normal soil cover (> the 2 ft used on standard earth covered magazines) will mitigate the roof debris hazard.

This roof design provides more containment of the blast wave than standard earth covered magazines. Exits are short tunnels which will choke the exit pressures, reduce the safe pressure distance in most directions, and reduce the total encumbered land area. However, the tunnel exits (which focus the blast wave) can also increase the safe pressure distance on the axis of the tunnel.

Objectives

Accurate methods do not exist for determining the HP Magazine internal and external loads, roof/soil cover breakup, and safe debris distance. Testing is necessary to improve and verify existing methods and to develop new analytical methods. Small-scale tests are required to inexpensively determine the effect of the many variables that effect the performance of the HP Magazine roof. The small-scale parameter tests will be used to verify the applicability of the existing analytical methods, and to provide data to improve the methods for the specific geometry of the HP Magazine. The small-scale tests are also necessary to show the feasibility of the concept for limiting safe hazard distances to about $40W^{1/3}$.

The objective of this test program is to determine the effect of roof & soil cover design parameters on safe debris and pressure distances.

The specific objectives are to:

- Determine the effect of soil cover depth, roof span and support type (center span full height wall vs. column support), tunnel exit conditions, charge density (W/V), and donor location on debris density vs. range.

- Determine the effect of tunnel exit conditions (area, number, and location) and W/V on external pressure vs. range and azimuth.

- Determine the breakup pattern and debris characteristics (launch velocity & angle, mass, and shape factor) of the roof and soil cover for use in verifying and improving analytical procedures.

Scope

Scale model testing (scale factor, $F_s = 1/10$) will be used to determine the effect of the key variables on safe debris range (scaled distance at which the debris density = 1 hazardous fragment per 600 ft^2) and safe pressure range (scaled distance at which the peak incident pressure = 1.2 psi). Geometric scaling (model dimensions = F_s * full-scale dimensions) will be used to properly scale most key parameters (gravity being the important exception). Geometric scaling (especially at the relatively large scale of 1/10) has been shown to be accurate for modeling the pressure environment. NEW scales as F_s^3. The scale model tests should also provide accurate debris launch angles and velocities. However, accurate prediction of full-scale debris mass, debris range, and roof breakup, will require test results from at least two scale model sizes. Analytical and empirical procedures will be used to convert the small-scale debris mass and distance results to predictions of full-scale response.

The key variables to be investigated are charge density (W/V), roof & soil weight, roof span length between walls, and roof edge conditions (free vs restrained). The scope of the test program is outlined in Table 1. The following parameters were held constant for all six tests:

- NEW = 10 lb TNT equivalent (W = 7.43 lb of Comp C-4 for Tests 1-5, and W = 7.35 lb of Comp C-4 for Test 6)

- Charge located in center cell of magazine

- One open tunnel exit at each end

The edges of the roof slabs were free to move upward in Tests 1-3, but were restrained in Tests 4-6. Soil cover depths of 0, 3.6, and 7.2 inches were used in the six tests. Test 6 used a half-width magazine (larger W/V ratio) to obtain higher reflected shock and gas pressure loads.

TEST SETUP

Test Site

The tests were conducted in the West Valley area of the Terminal Effects Research and Analysis Group (TERA) Field Laboratory located at the New Mexico Institute of Mining and Technology (NMIMT) in Socorro, New Mexico. The site dimensions are shown in Figure 1. The outside boundaries were determined from the debris recovery and pressure gauge line requirements. Debris recovery areas and pressure gauge lines are also shown in Figure 1. The area was re-bladed and re-rolled prior to the test program. The test site was cleared of most debris between each test.

Test Fixture

A reusable magazine test fixture (with replaceable cell walls and center span roof supports) was provided to conduct the 1/10-scale tests of HP Magazine roof specimens (see Figure 2). The reusable fixture consists of 4-ft thick by 4-ft high (outside dimension) reinforced concrete walls poured monolithically with a 2'-6" thick reinforced concrete floor. The inside of the walls were lined with 3/8-in. thick steel plate. The fixture was designed as a partial containment cubical with venting through the open tunnel exits and the frangible roof and soil cover. The blast loads acting on the inside faces of the walls were resisted by transfering the loads into the floor which was heavily reinforced with two horizontal layers of #6 "tension" bars spaced @ 10 in. in each direction. Each end of these continuous "tension" bars was bent 90° upward into the wall. To help transfer the load downward into the floor, #6 vertical bars spaced at 10 in. were located near the inside face of the four walls and crossed through the potential horizontal shear crack. The test fixture was also strengthened by placing three #6 flexural bars in each face of the four walls. These flexural rebars were tied together with #4 closed-ties spaced at 18 in. No diagonal rebars were used at any of the sidewall/endwall, sidewall/floor, or endwall/floor corners. The top of the fixture was flat to simply support a 3-in. wide roof slab bearing surface. 1-in. diameter embedded hook bolts were spaced at 12 in. to provide translational/rotational edge restraint in the slab for Tests 3 through 6. Each end wall has two 16-in. diameter circular exits. However, for all six tests, a 3/4-in. thick steel plate closed off one exit in each end wall.

Directly under the donor explosive, a 9-in. x 12-in. rectangular cavity was formed in the floor. This cavity was partially filled with sand and then a 3-in. thick steel plate was placed flush with the surrounding concrete floor to mitigate cratering and provide a reflecting surface.

The roof in Tests 1 through 5 was supported by a continuous 2x4 wood beam resting on 4x4 (column) wood supports to the floor. Test 6 setup required a full-height sand-filled wooden wall center support. The 19-in. by 19-in. donor cell (inside dimensions) was simulated with 3-in. thick x 9.5-in. high unreinforced concrete walls (Figure 2). A photograph of the completed test fixture at TERA is shown in Figure 3.

Roof Specimens

The reinforced concrete roof slabs were built as shown in Figure 4. The test plan called for a concrete mix proportioned for a 28-day compressive strength of 4,000 psi. However, due to expected time schedule constraints, a high-early strength concrete mix was chosen to obtain the strength in 14 days. Figure 5 shows the distribution of the fine and coarse aggregate used in the following mix:

0.60/1.0/1.30/2.28

These numbers denote relative weights of water, cement, fine and coarse aggregate. Each slab was tinted with a different colored admixture to facilitate debris analysis. For some unknown reason, the strength results of concrete test cylinders cast during the pouring of the six roof slabs were consistently less (13-37%) than 4,000 psi.

The reinforcing steel in the 6'-6" by 6'-6" area directly above the donor explosive (as shown in Figure 4) modeled the flexural and shear steel in a full-scale static design for a roof with 4 ft of soil cover. To reduce cost, the concrete x-section "B" away from the donor charge did not include the shear stirrups. These areas of the slab were not expected to breach and therefore the shear steel requirements were relaxed. The flexural strength in these areas was unchanged. In the full-scale design, the required main flexural steel is as follows:

Grade 60, #9 rebar	
Static design yield stress, f_s	66,00 psi
Bar diameter, d	1.128 in.
Bar area, A	1.0 $in.^2$
Bar spacing, s	10 in.
Distance between centroids of compr. & tens. rebar, d_c	19.1 in.

Ideally, the model reinforcement should be made of the same material with the following 1/10-scale properties:

Bar diameter, d	0.113 in.
Bar area, A	0.010 $in.^2$
Bar spacing, s	1.0 in.
Distance between centroids of compr. & tens. rebar, d_c	1.91 in.

In designing the model structure, compromises were made in rebar strength, size and spacing to reduce costs and simplify construction, while keeping the moment capacity (i.e., $A f_s d/s$) approximately unchanged. The final model main reinforcement selected was a carbon steel, welded wire cloth with the following properties:

Static yield stress, f_s	86,636 psi
Bar diameter, d	0.120 in.
Bar area, A	0.0113 $in.^2$
Bar spacing, s	1.12 in.
Distance between centroids of compr. & tens. rebar, d_c	1.85 in.

The model shear reinforcing was double leg stirrups made from 20 gauge 60 ksi wire (which corresponded to single leg #4 stirrups at full-scale).

Soil Cover

The soil cover used in all tests was uncompacted dry sand. A uniform density of 107.5 pcf was consistently achieved by simply dropping the sand from a skip loader onto the roof slabs. A photograph of a roof slab with soil cover just prior to testing is shown in Figure 6.

Explosive Donor

Rectangular Composition C4 explosive charges were constructed to simulate (1/10-scale) the full-scale magazine MCE of 10,000 lb TNT. The Net Explosive Weight (NEW) for each test was 10.0 lb TNT equivalent, based on gas pressure equivalency. The weight of Composition C4 required to produce the same peak gas pressure as 10.0 lb of TNT was determined from Reference 3 and is shown below:

Test No.	W (lb)	Height (in.)	Width (in.)	Length (in.)
1-5	7.43	4	5	6.3
6	7.35	4	5	6.2

The TNT equivalencies for the C4 are 1.35 for Tests 1-5 and 1.36 for Test 6. The bottom of the explosive charge was located 2.2 inches off the steel floor plate.

Data Requirements

Airblast. The airblast instrumentation consisted of 23 gauge stations: nineteen stations external to the test fixture and four stations internal to the test fixture. Piezo-resistive pressure transducers were used at all stations except the two piezo-electric PCB transducers used at Stations SP-1 and SP-2. The signals from the transducers were recorded on magnetic tape by Honeywell Model 101 14-track FM tape recorders operating at 120 ips. The system bandwidth was 80-kHz. A programmable sequence-control timer detonated the charge and operated the recording system. The data for each test were later digitized, processed, and plotted.

The external pressure gauges were surface mounted to measure incident blast overpressures along gauge lines to the front ('F'), on a diagonal ('D'), to the side opposite the center of the test fixture ('S'), and to the back ('B'). External pressure gauge locations are shown in Figure 7.

The internal pressure gauges were located inside the test fixture to measure the shock and gas overpressures. Two of the gauges measured the internal shock overpressures just inside the front and back tunnel exits at the cylinder bottoms. The other two gauges were located in opposite long walls of the test fixture to measure the gas pressure inside the fixture. The gauge was thread-mounted at mid-height of the wall so the gauge diaphragm was flush with the face of the wall. A perforated steel filter was placed over the diaphragm to protect it from internal debris and attenuate the shock pressures. The internal pressure gauge locations are also shown in Figure 7.

Photographic Coverage. Five high-speed motion picture cameras and one real-time video camera were used in each test. The high-speed cameras (Nos. 1 through 5) were used to measure initial debris angle and velocity. The real-time camera (No. 6) was used to cover the overall event. Camera locations are shown in Figure 8.

Debris Recovery. Debris was recovered and characterized by TERA. The debris recovery zones were two 5-degree sectors to the front and side of the test fixture, as shown in Figure 9. The recovery sector to the side began at 40 ft from the inside wall of the test fixture and extended to 460 ft. The recovery sector to the front began at 41-3/4 ft from the inside wall of the test fixture and extended to 241-3/4 ft. A concrete pad was used in the first 200 ft of each 5-degree sector. The debris recovery zones were formed by the 5-degree boundaries and radii at 20-ft spacings. All debris was collected in the recovery zones. Debris passing through a 3.35 mm sieve was not analyzed. A sieve analysis (using 4.75mm and 6.35 mm sieves) was run on debris retained by the 3.35 mm sieve but passed by a 9.50 mm sieve. The debris retained by the 3.35 mm sieve was counted and collectively weighed. The debris retained by the 4.75 mm and 6.35 mm sieves was counted and individually weighed. The debris retained by the 9.5 mm sieve was individually weighed, and measured (length, width, and thickness).

Individual debris outside the recovery zones was mapped by TERA. About 50 pieces of the largest debris and at the greatest distances were recovered for each test. This debris was categorized by size as described above for the debris retained by a 9.50 mm sieve.

TEST RESULTS

Reference 4 contains the digitized data for the internal and external pressure gauges of all six tests. Impulses were obtained by numerically integrating the digitized pressure data. No filtering of the data was employed. The data for each test are referenced to a common zero time (Time of Detonation) and are displayed with time in milliseconds as the abscissa. A typical data record is shown in Figure 10. The values of the measured peak pressures in all six tests are listed in Table 2.

Reference 4 also contains the complete records of the debris collected from all six tests.

High speed films showing test results are in the possession of NCEL.

Observed Structural Response/Breakup

Review of the videos/high-speed films combined with visual studies of the condition of the tested roof slabs produced the following general observations:

- The roof slabs in all six tests were lifted off the test fixture as a rigid body and propelled straight upward. The maximum vertical lift occurred in Test 1 (no soil cover) and the minimum occurred in Tests 3, 5 and 6 (7.2 inches soil cover).
- The final resting positions for all six tests were within the boundaries of the test fixture.
- Breaching of the roof slabs occurred directly above the location of the explosive charge in all six tests. The amount of breaching was inversely proportional to the soil cover depth.

Photographs of the six tested slabs are contained in Figures 11 through 20.

Pressure Data Analyses

The pressure outside the test fixture consists of two components: (1) directional leakage pressure from the tunnel exits and (2) leakage pressure through the breached roof and soil cover. A detailed explanation of the methods developed to calculate the pressures from these two physical phenomena are contained in Reference 4.

The method used to calculate the external pressure from the tunnel exits was recently developed by the U.S. Army Ballistics Research Laboratory (Reference 5). The following relationship is applicable for magazines with one tunnel exit:

$$p_o = 1.733[d(W/V)^b]^{0.83}(A_t/A_c)^{0.19}[R_o/(1.173\ D)]^{-1.35} \tag{1}$$

where,

p_o = peak pressure at distance R_o, psi

R_o = distance from opening along centerline axis (0^o line), ft

W = explosive storage weight, lb

V = total volume of chamber (test fixture) and tunnels, ft^3

for $W/V \le 0.025$,	$d = 4000$ $b = 0.82$
for $0.025 < W/V < 0.07$,	$d = 945$ $b = 0.43$
for $W/V \ge 0.07$,	$d = 2675$ $b = 0.82$

A_t = cross-sectional area of the tunnel opening, ft^2

A_c = cross-sectional area of the chamber (test fixture), ft^2

D = equivalent circular cross-sectional diameter of tunnel, ft

This equation is partially based on the following two equations for peak gas pressure inside the chamber (p_c) and peak pressure at tunnel exit (p_x):

$$p_c = d(W/V)^b \tag{2}$$

$$p_x = 1.733(P_c)^{0.83}(A_t/A_c)^{0.19} \tag{3}$$

The equation for p_o along any line "a" degrees from the 0^o line is given as:

$$p_o = 1.733[d(W/V)^b]^{0.83}(A_t/A_c)^{0.19}[R_a/(1.173\ D\ F_a)]^{-1.35} \tag{4}$$

where,

R_a = distance from opening along "a" line, ft

F_a = $[1 + (a/56)^2]^{-0.741}$

Exit pressures for multiple tunnels (2) were calculated, at a given range and azimuth, by conservatively adding the peak pressures calculated from Equation 4 for each tunnel exit.

The method used to calculate the external pressure from the leakage through the breached roof and soil cover is based on procedures (Reference 6) developed by the U.S. Army Waterways Experiment Station (WES). The following relationship is for fully-coupled buried charges (explosive charge in direct contact with soil cover):

$$p_o = 3.51\ (h/W^{1/3})^{-2.7}\ (R/W^{1/3})^{-1.06} \tag{5}$$

where,

p_o = peak pressure at distance R, psi

h = cover depth, ft

R = horizontal distance from explosive source, ft

W = explosive weight, lb

However, our tests were considered as decoupled buried charges (air gap between charge and soil cover). WES has determined the following coupling factor (C_{cf}) to relate fully-coupled and decoupled buried charges:

$$C_{cf} = 0.03358\ (W/V)^{0.4555}$$

where,

W = decoupled explosive weight, kg

V = total chamber volume, m^3

The equivalent fully-coupled charge weight is:

$$W_{cf} = C_{cf} W$$

Calculation of W_{cf} allows the use of the relationship (Equation 5) developed for fully-coupled charge weights.

The predicted peak gas and tunnel exit pressures were calculated from Equations 2 and 3 and listed below:

Pressure Measurement	Peak Pressure (psi) for Test No,	
	1 - 5	6
Gas Pressure, p_c	287.1	460.6
Exit Pressure, p_x	133.4	225.3

The gas pressure data (GP gauges) was very poor and not usable. The tunnel exit pressure data (SP gauges) was much better in providing values of peak pressure and duration. Apparently, the environment inside the test fixture (shock, temperature, and debris) was too severe for the GP gauges. For the next Phase II test series, the protection of the GP gauge diaphragm will be enhanced. Statistically, the average and standard deviation of the peak exit pressures are listed below:

Quantity	Test Nos. 2 - 5	Test No. 6
Average Pressure, psi	399	432
Standard Deviation, psi	60	33

These values are much greater than predicted.

The predicted peak external pressures from the two methods were calculated in Reference 4 for all six tests. Although the peak pressures from these two components will occur at different times, they were added to obtain the conservative test predictions listed in Table 3. Because all six tests had a front and back tunnel, the predicted pressures to the front and back are identical. As an example, the predicted pressures for Test 3 are plotted versus range in Figure 21 for the four directions (i.e., front, diagonal, side, and back). As a means of reference, the peak pressure from a hemispherical surface burst (Reference 7) is also shown on this figure. The measured external peak pressures for Test 3 listed in Table 2 are also plotted in Figure 21. The test data for each test are very similar and always less than the surface burst curve. Except for Test 1 (no soil cover), the close-in pressures to the side of the test fixture were greatly reduced. Apparently, the absence of a soil cover allowed a significant amount of pressure to vent through the breached concrete roof immediately above the explosive charge and reach the nearby side pressure gauges. For Test 1, the measured peak pressures to the front, back, and diagonal were less than predicted, while the pressures to the side were greater than predicted. Good agreement of the measured and predicted peak pressures occured for Tests 2 through 5. For Test 6, the measured peak pressures were greater than predicted. Better agreement would have occured if the full volume of the test fixture, and not the half volume, was used in the prediction modeling. Apparently, the 3-1/2 in. thick sand-filled full-height center wall was breached immediately after detonation and thus the actual test setup modeled a full-volume test fixture.

Debris Data Analyses

Debris Outside Recovery Sectors. Analyses of the debris collected outside the recovery sectors indicate that the maximum debris distance is reduced by increasing the soil cover depth. This trend is shown in Figure 22 for Tests 4 (3.6 in. soil cover) and 5 (7.2 in. soil cover).

Debris Within Recovery Sectors. An example of the debris areal distribution by zone is shown in Table 4 for the side recovery sector of Test 1. This table contains all debris with mass greater or equal to the critical mass* of 0.000375 lb (2.6 grains). This 1/10-scale debris data was scaled up by applying the trajectory relationship between a 1/10-scale debris and full-scale debris. This relationship is graphically shown in Figure 23 and is valid for a 1/10-scale mass of 0.038 lb (average mass of debris collected in the large debris mapping area) at an initial angle of 40° above the horizontal. The full-scale debris areal number density, calculated as the cumulative number of debris per 600 ft^2, is listed in this table and shown in Figure 24. The debris densities for all six tests to the side and front directions are shown in Figures 24 and 25, respectively. The debris hazard range is defined to be that range beyond which the areal number density of hazardous fragment is one per 600 ft^2 or below. The hazardous range for

* Trajectory (Reference 8) calculations found that critical debris with a mass of 0.000375 lb or larger are hazardous (58 ft-lb) upon impact.

all six tests were graphically obtained from the above figures and are listed in Table 5 and plotted in Figures 26 and 27 versus full-scale soil cover depth. Also shown in these figures are the safe debris ranges predicted by the "Building Debris Hazard Prediction Model, DISPRE" (Reference 9).

CONCLUSIONS

The measured safe pressure distances (i.e., distance from the test fixture exterior that the peak pressure decays to 1.2 psi) to the front, diagonal, and side directions for all six 1/10-scale tests are listed in Table 6. Neglecting Test 1 and the side direction of Test 5, the safe distances varied from 41.8 to 50.8 ft. The corresponding safe pressure distances for a full-scale HP Magazine would vary from 418 to 508 ft. This is still less than the 862 ft ($40\ W^{1/3}$) required by Reference 1 for an MCE of 10,000 lb NEW.

The external pressures predicted by the methods outlined in this paper compared very well with the measured pressures to the front, diagonal, and back directions. Their use in predicting the safe pressure distances in these directions would be conservative. However, comparisons of the predicted and measured pressures to the side were not as good. Their use in predicting the safe pressure distance in the side direction would be unconservative. At peak pressures less than about 1.2 psi, the measured peak pressure to the side vs. range curves for the five tests with soil cover (i.e., Tests 2 - 6) are very close to the curves for the front direction. Therefore, it is recommended that the safe pressure distance to the side be set equal to the safe distance to the front. The configuration of future Phase II small-scale tests will change from two tunnel exits (i.e., one at each end) to one tunnel exit. Phase II test results may result in changes to prediction methods recommended in this report.

The full-scale safe debris distances based on the worse-case measured 1/10-scale test data listed in Table 5 are shown below:

Full-Scale Soil Cover, h_s (ft)	Full-Scale Safe Debris Distance, (ft)
0	891
3	800
6	542

These values are all less than the 1,250 ft required by Reference 1.

It is concluded that the HP Magazine concept can mitigate the fragment and debris hazard and that the required safe pressure and debris hazard ranges will significantly reduce the total area encumbered by ESQD arcs.

REFERENCES

1. Naval Sea Systems Command. Technical Manual NAVSEA OP 5, Volume 1: Ammunition and Explosives Ashore. Fifth Revision, 1 Aug 1990.

2. Naval Civil Engineering Laboratory. Technical Memorandum 51-89-12: Feasibility of High Performance Magazine, by W.A. Keenan and J.E. Tancreto. Port Hueneme, CA, July 1989.

3. Naval Surface Warfare Center. Technical Paper: INBLAST -- A New and Revised Computer Code for the Prediction of Blast Inside Closed and Vented Structures, by Paul E. Montanaro and Michael M. Swisdak Jr. Published in Seminar Proceedings, 24th DDESB Seminar, St. Louis, MO, Aug 1990.

4. Naval Civil Engineering Laboratory. Technical Report (to be published): Small-Scale High Performance Magazine Roof and Soil Cover Feasibility Test Report, by Robert N. Murtha. Port Hueneme, CA.

5. U.S. Army Ballistics Research Laboratory. Briefing to DDESB Secretariat: Proposed Quantity - Distance Criterion for Accidental Explosions in Underground Storage Sites, by Charles Kingery, George Coulter, and Gerald Bulmash. Aberdeen, MD, Feb 1988.

6. U.S. Army Waterways Experiment Station. Paper presented to DDESB Tri- Service Committee on Underground Storage: Cover Vented Overpressure, by Charles E. Joachim. Vicksburg, MS, May 1990.

7. U.S. Army Ballistics Research Laboratory. Technical Report ARBRL-TR-02555: Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst, by C. Kingery and G. Bulmash. Aberdeen, MD, 1984.

8. Naval Surface Warfare Center. Technical Paper: TRAJ -- A Two Dimensional Trajectory Program For Personal Computers, by Paul E. Montanaro. Published in Seminar Proceedings, 24th DDESB Seminar, St. Louis, MO, Aug 1990.

9. Southwest Research Institute. Technical Report: Building Debris Hazard Prediction Model, by Patricia M. Bowles, Charles J. Oswald and Luis M. Vargas. San Antonio, TX, Feb 1991.

Table 1. Schedule of Tests.

Test No.	Charge Weight[1] of Comp C-4, W (lb)	Roof/Soil Cover Configuration	Roof[2] Weight (psf)	Volume	Roof Edge Conditions
1	7.43	2.4" roof	30	Full	Free
2	7.43	2.4" roof + 3.6" soil	63	Full	Free
3	7.43	2.4" roof + 7.2" soil	96	Full	Free
4	7.43	2.4" roof + 3.6" soil	63	Full	Restrained
5	7.43	2.4" roof + 7.2" soil	96	Full	Restrained
6	7.35	2.4" roof + 7.2" soil	96	1/2	Restrained

[1] The Net Explosive Weight (NEW) for each test is 10.0 lb TNT equivalent, based on gas pressure equivalence

[2] Roof density = 150 pcf; soil density = 110 pcf

Notes:

- Both exits at each end are 16" diameter (Area = 201 in^2)
- Test fixture volume = 148.5 ft^3 in Tests 1-5
- Test fixture volume = 74.25 ft^3 in Test 6

Table 2. Measured Peak Pressures

Gauge No.	Peak Pressure (psi) for Test No,					
	1	2	3	4	5	6
SP-1	308.1	339.9	432.2	430.0	449.7	454.9
SP-2	395.4	327.2	470.5	320.4	418.6	407.7
GP-1	332.0	234.2	-----	274.2	293.6	-----
GP-2	565.9	357.8	-----	360.8	609.1	-----
F-1	----	4.48	4.90	4.55	4.47	5.00*
F-2	2.06	2.25	2.40	1.92	2.33	2.45
F-3	1.52	1.55	1.67	1.47	1.61	----
F-4	0.84	0.88	0.90	0.82	0.71	0.87
F-5	----	0.67	0.62*	0.69	0.55	0.60*
F-6	0.40*	----	----	0.47	0.40	0.42
F-7	0.22	0.25	0.25*	0.30*	0.25	0.23
D-1	1.30	1.39	1.56	1.28	1.37	1.49
D-2	0.79	0.86	0.97	0.80	0.84	0.97
D-3	0.54	0.57	0.67	0.63	0.58	0.66
D-4	0.37	0.45	0.48	0.47	0.42	0.47
S-1	8.89	1.57	1.80	1.64	1.63	1.87
S-2	6.52	1.15	----	1.32	1.33	1.46
S-3	3.86	1.38	1.23	1.16	1.12	1.33
S-4	1.54	1.22	1.24	1.24	1.12	1.43
S-5	0.95	0.50	0.49	0.54	0.54	0.72
B-1	0.93	1.05	0.90	0.79	0.77	1.00
B-2	0.44	0.52	0.43	0.44	0.48	0.49
B-3	0.25	0.30	0.28	0.25	0.28	0.29

* Adjusted for zero shifts or excessive spike

Table 3. Predicted Peak External Pressures

Location		Peak Pressure (psi) for Test No,			
Azimuth (Degree)	Range (ft)	1	2 & 4	3 & 5	6
Front (0)	20	5.59	4.56	4.46	7.51
	30	3.38	2.67	2.60	4.39
	40	2.38	1.84	1.79	3.00
	55	1.60	1.21	1.17	1.97
	75	1.09	0.80	0.77	1.30
	100	0.77	0.55	0.53	0.88
	150	0.46	0.32	0.31	0.52
Diagonal (30)	40	2.03	1.48	1.43	2.41
	55	1.39	0.99	0.95	1.60
	75	0.96	0.66	0.63	1.06
	100	0.67	0.45	0.43	0.73
Side (90)	15	3.44	1.66	1.48	2.50
	20	2.68	1.39	1.26	2.13
	30	1.83	1.00	0.92	1.56
	50	1.09	0.61	0.56	0.93
	75	0.70	0.39	0.35	0.60
Back (180)	55	1.60	1.21	1.17	1.97
	100	0.77	0.55	0.53	0.88
	150	0.46	0.32	0.31	0.52

Table 4. Debris Density in Side Recovery Sector for Test 1.

Zone Nomenclature	1/10 - Scale			Full-Scale		
	Range,[1] R_z (ft)	Number Debris, N	Cumulative Number Debris, N_T	Range,[2] R_z (ft)	Area,[3] A_z (ft^2)	Debris Density (#/600 sf)
S21	460	0	0	2829.0	52,811	0.00
S20	440	1	1	2609.0	49,344	0.01
S19	420	0	1	2385.0	44,710	0.01
S18	400	1	2	2163.2	37,130	0.03
S17	380	1	3	1959.9	35,015	0.05
S16	360	3	6	1747.0	28,501	0.13
S15	340	3	9	1552.7	24,159	0.22
S14	320	2	11	1367.0	19,819	0.33
S13	300	3	14	1193.8	15,990	0.53
S12	280	2	16	1033.7	12,622	0.76
S11	260	1	17	887.8	10,119	1.01
S10	240	4	21	751.4	8,127	1.55
S9	220	8	29	632.3	6,558	2.65
S8	200	14	43	518.9	3,863	6.68
S7	180	30	73	438.3	3,300	13.27
S6	160	29	102	357.6	2,670	22.92
S5	140	25	127	278.7	1,270	60.00
S4	120	67	194	231.6	1,076	108.18
S3	100	120	314	184.5	882	213.61
S2	80	130	444	137.4	688	387.21
S1	60	115	559	90.3	313	1,071.57

[1] Distance from roof edge to outside edge of zone

[2] Obtained from Figure 37

[3] $A_z = 2 \tan 2.5^\circ (R_z - R_{z-1})(R_z + 30)$; for Zones S1 thru S10

$A_z = 2 \tan 2.5^\circ (R_z - R_{z-1})[(R_z + R_{z-1} + 60)/2]$; for Zones S11 thru S21

Table 5. Full-Scale Safe Debris Distances

Test No.	Measured Safe Debris Distance (ft) to,		Predicted Safe* Debris Distance (ft)
	Side	Front	
1	891	718	1,050
2	323	661	599
3	133	542	436
4	800	661	599
5	239	506	436
6	236	218	436

* From "DISPRE"

Table 6. Measured 1/10-Scale Safe Pressure Distances*

Azimuth	Safe Distance (ft) for Test No,					
	1	2	3	4	5	6
Front	45.4	46.2	47.4	44.7	44.8	45.6
Diagonal	42.1	44.1	47.7	41.8	43.6	47.0
Side	57.0	45.7	46.0	46.1	20.8	50.8

* Distance from the exterior of the test fixture that the peak pressure decays to 1.2 psi.

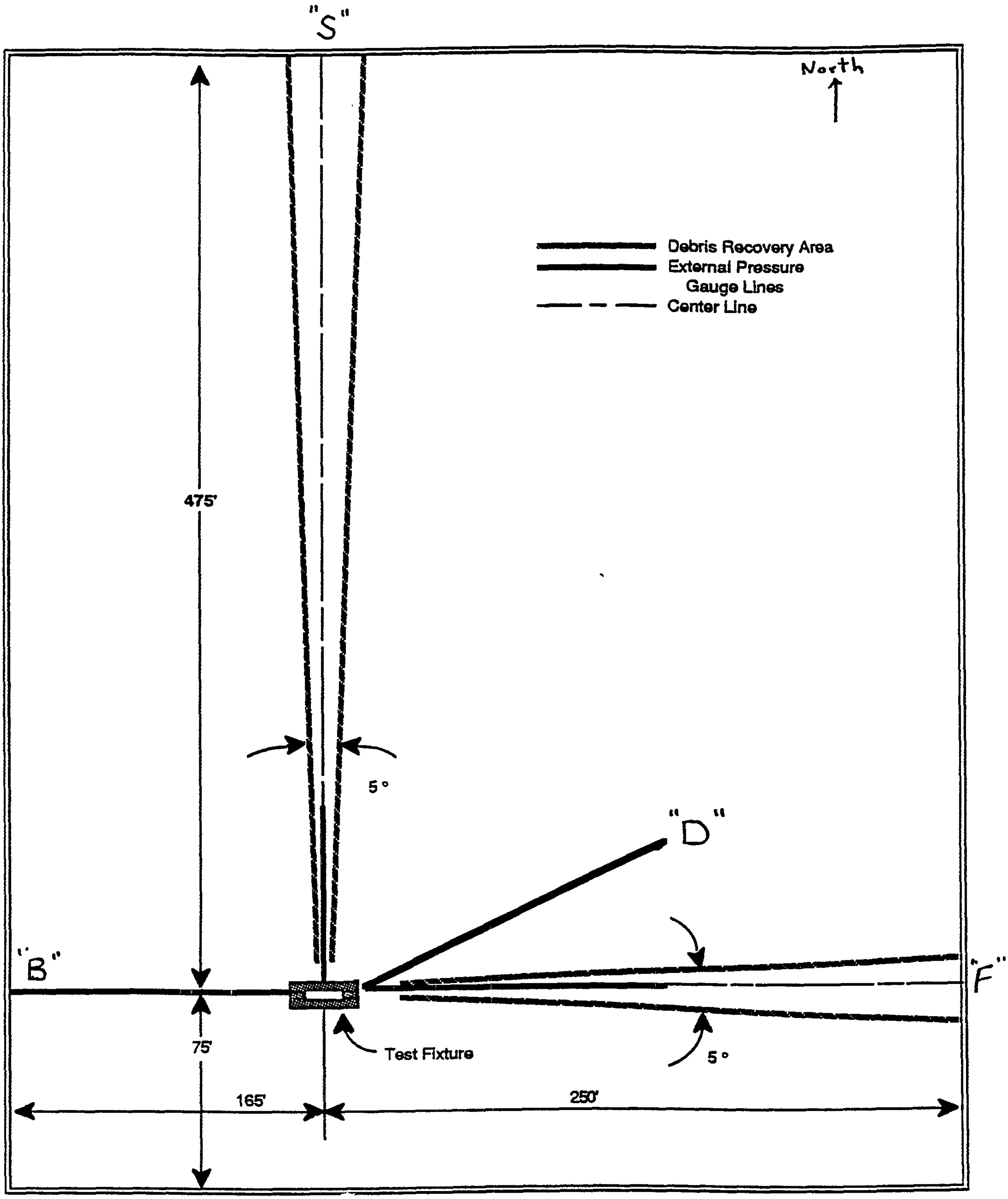

Figure 1. Overall site dimensions.

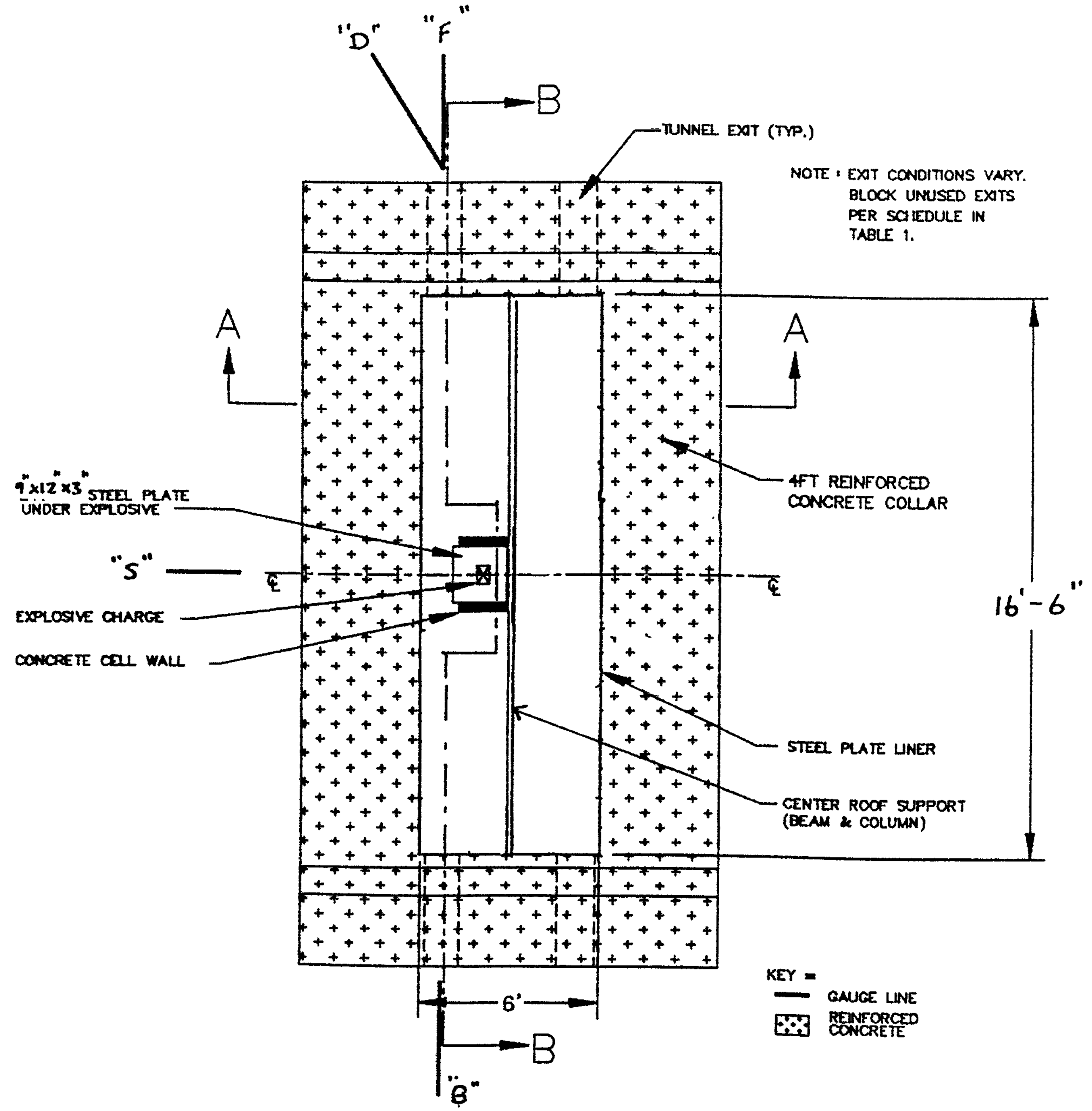

FIGURE 2a. TEST FIXTURE : PLAN VIEW (ROOF NOT SHOWN)

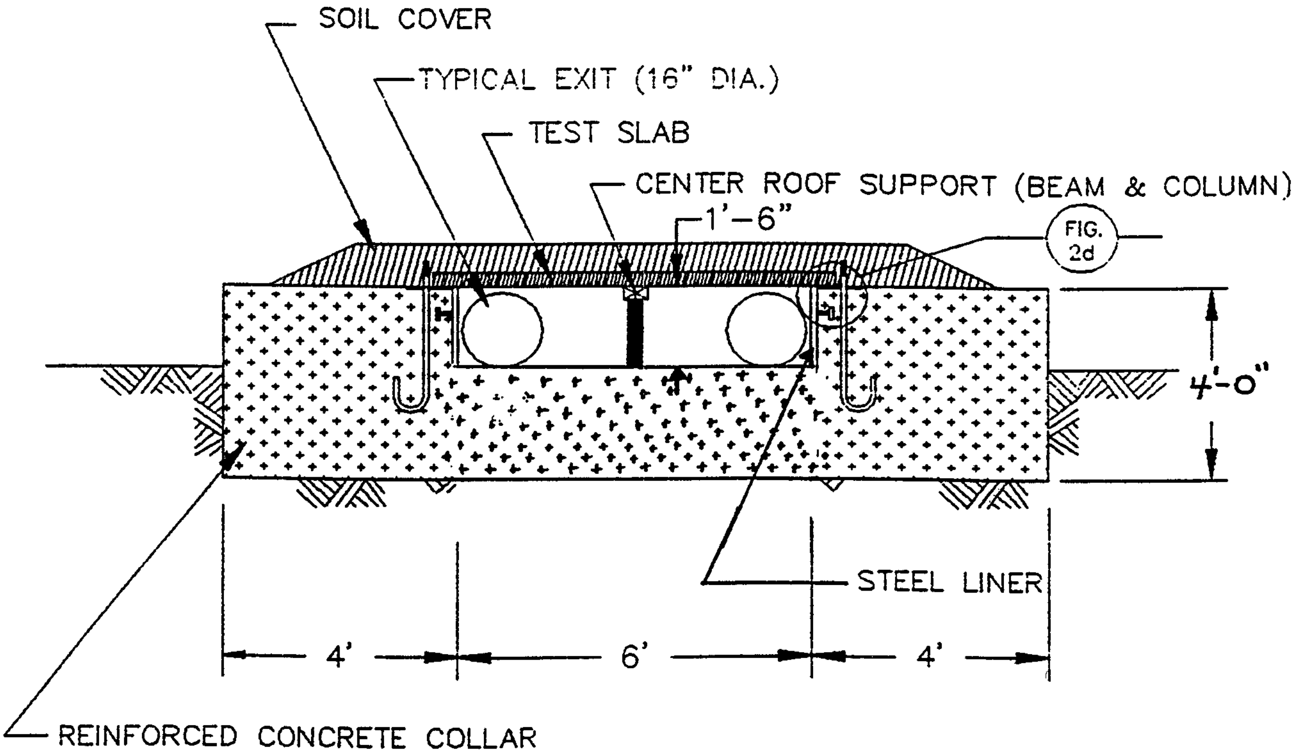

FIGURE 2b. TEST FIXTURE : SECTION A-A

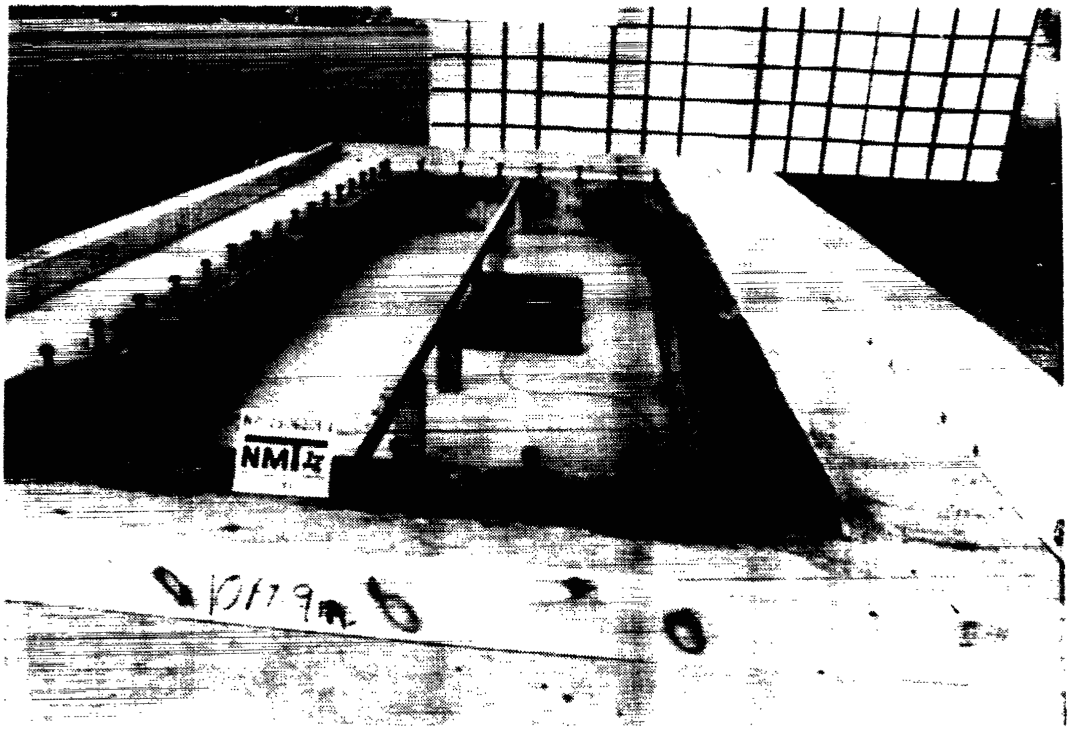

Figure 3. Test fixture interior.

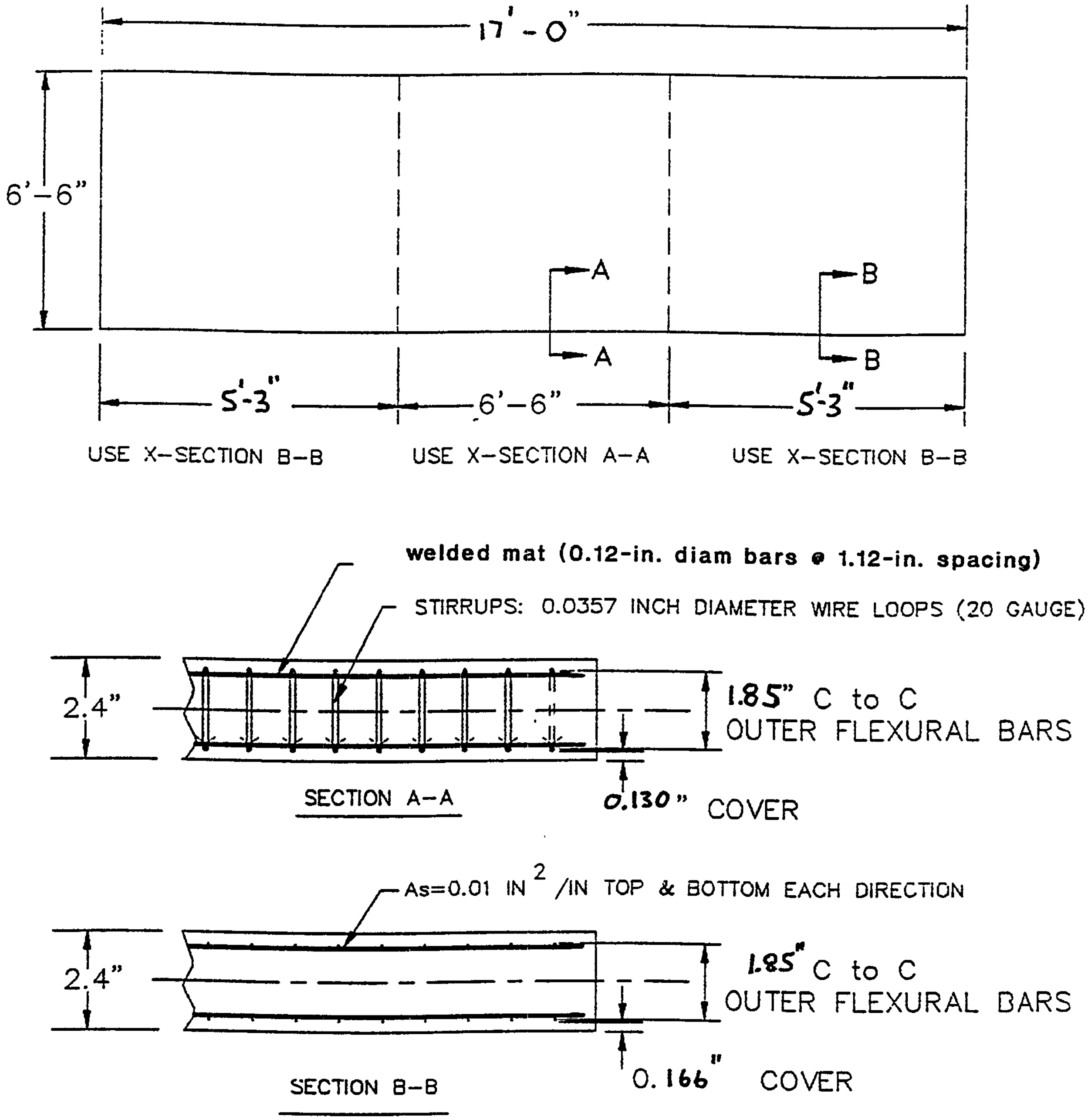

FIGURE 4. ROOF SLAB TEST SPECIMEN

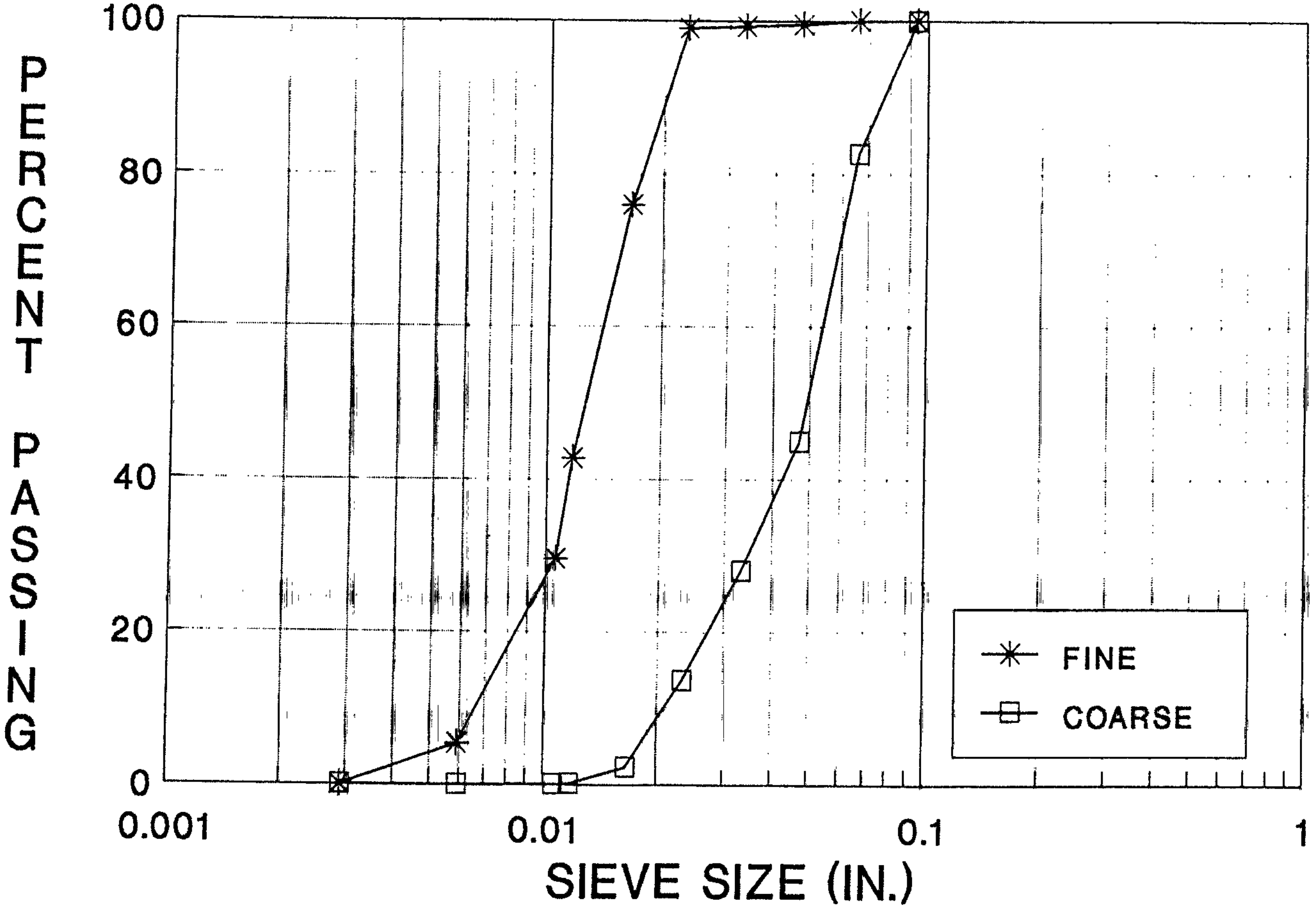

Figure 5. Aggregate distribution for 1/10-scale model concrete mix.

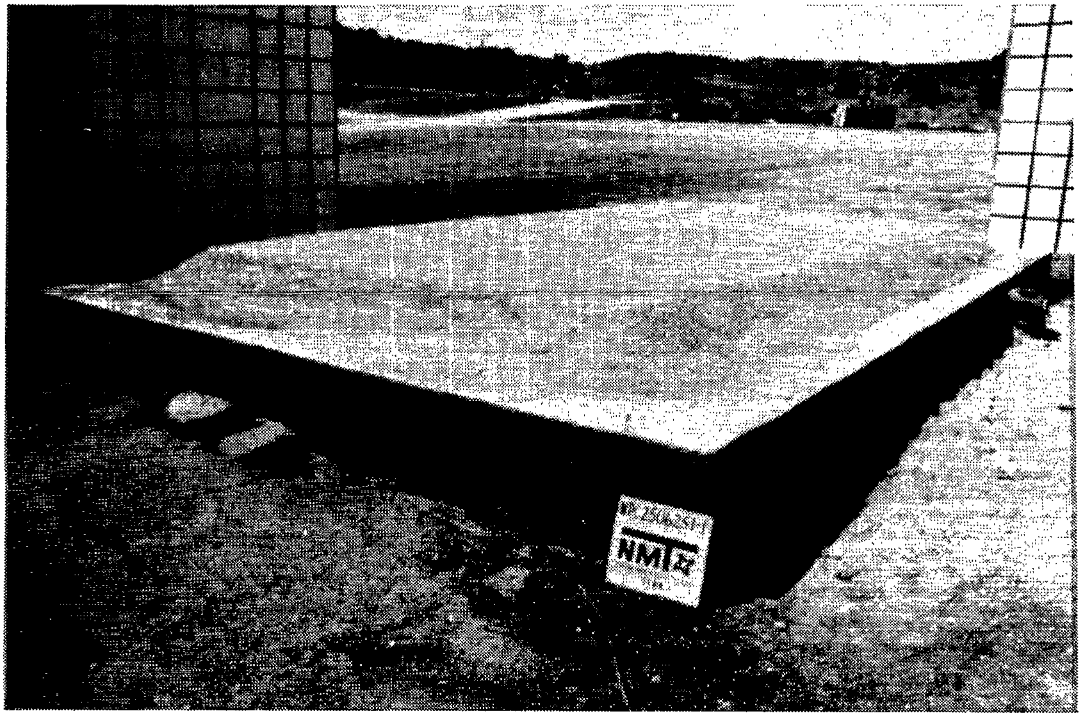

Figure 6. Roof specimen with soil cover.

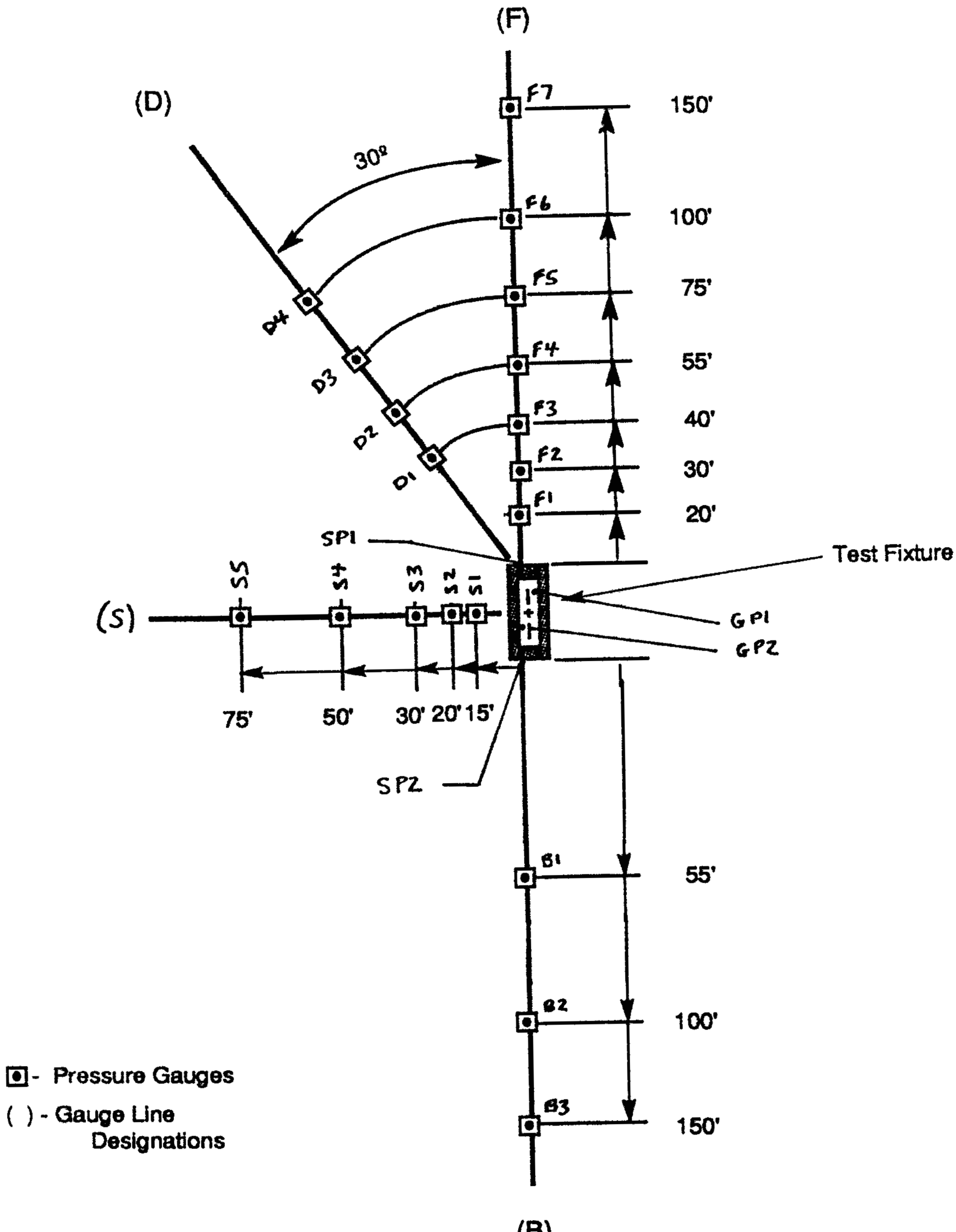

Figure 7. Pressure gauge locations.

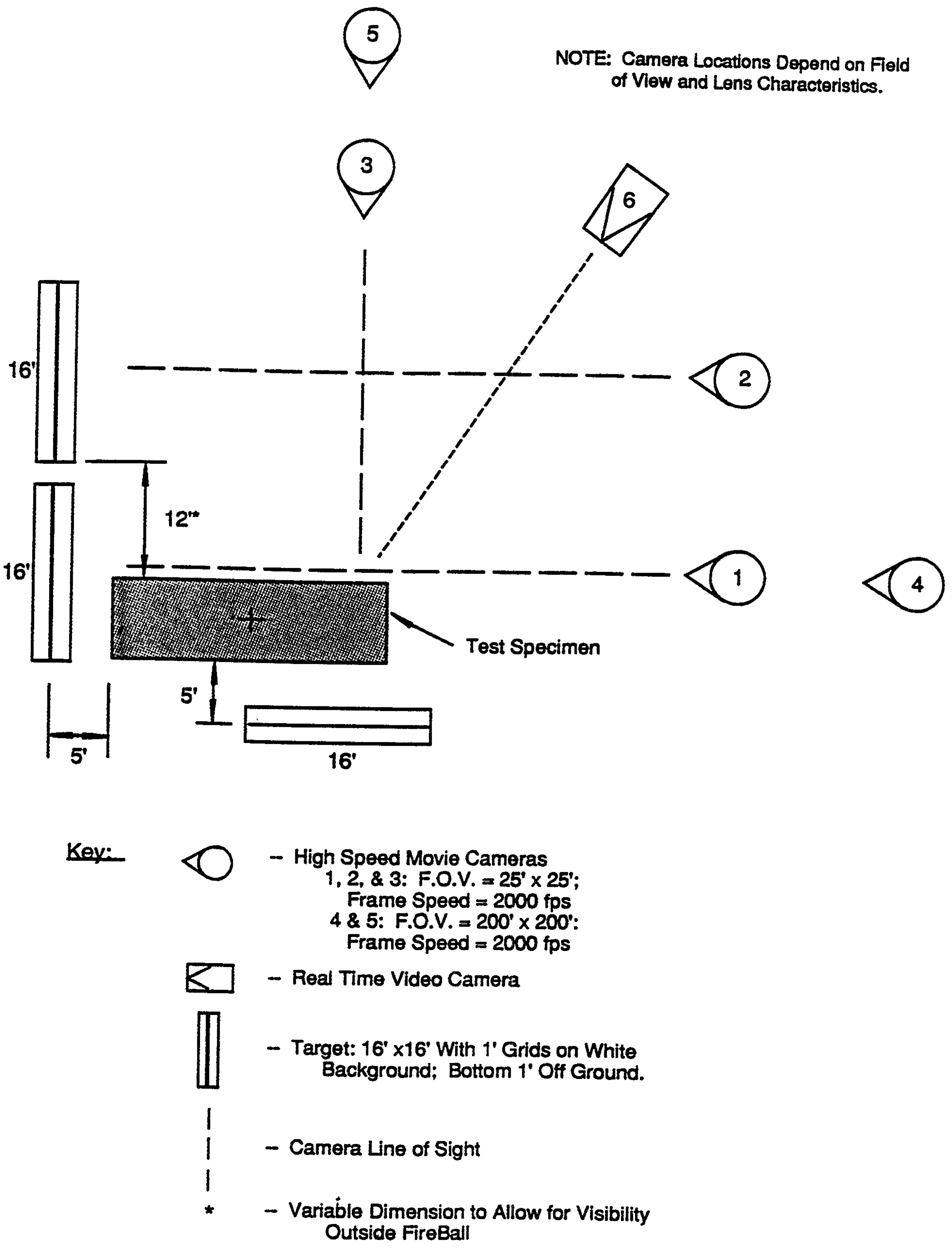

Figure 8. Camera locations.

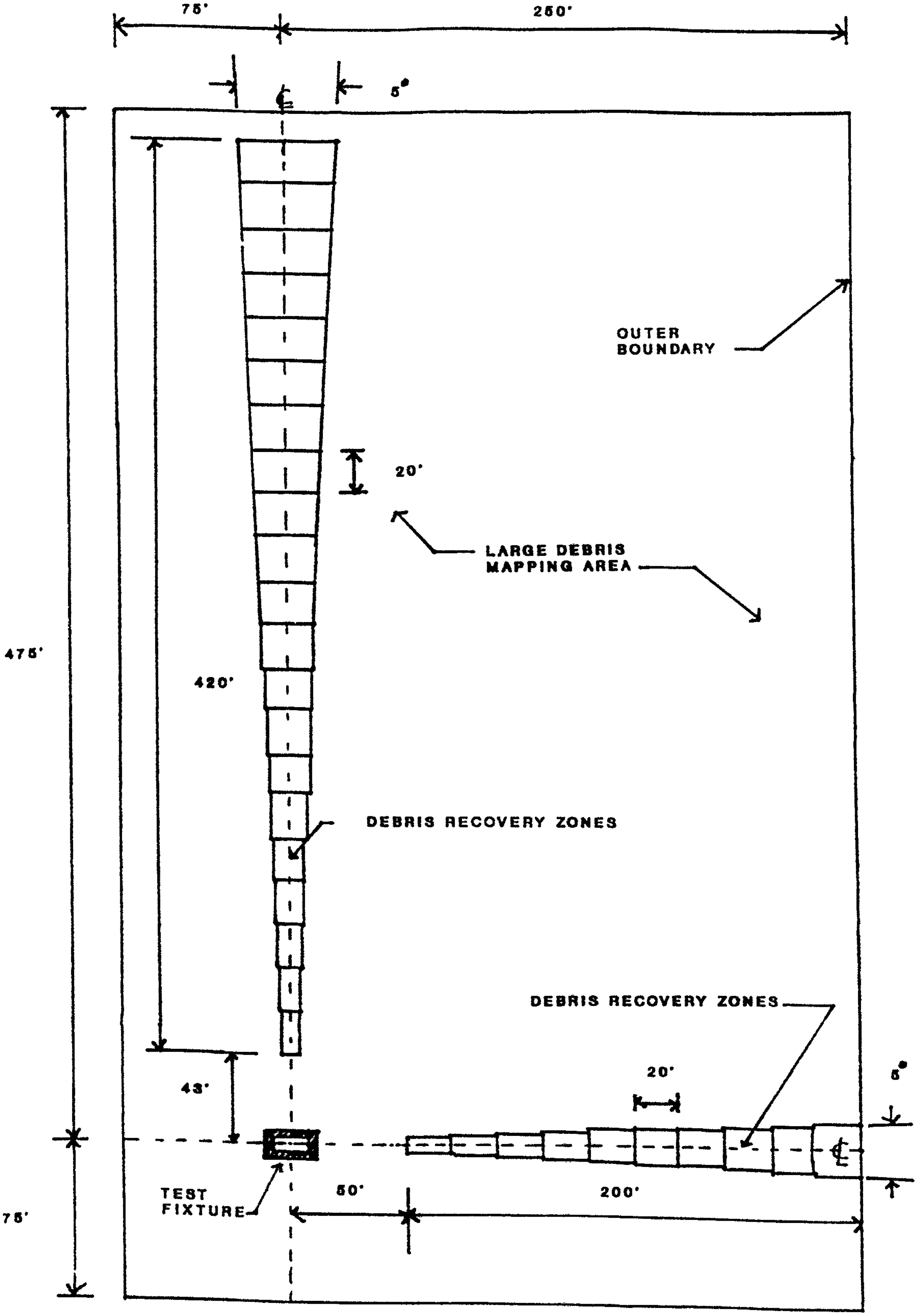

Figure 9. Debris recovery zones.

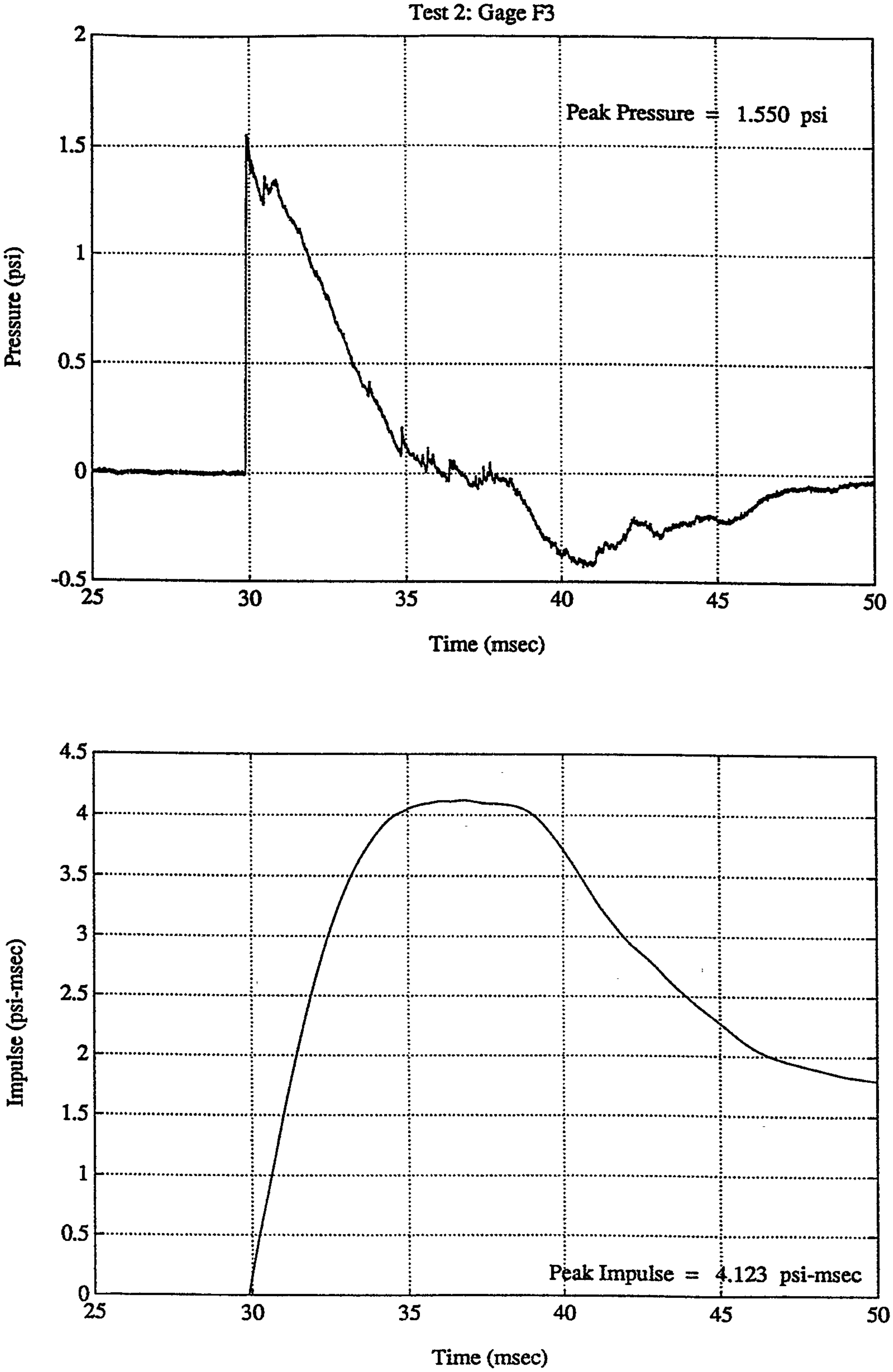

Figure 10. Pressure and impulse time histories for Guage F3, Test 2.

Figure 11. Post-test overall view of Test 1 roof.

Figure 12. Post-test close-up view of Test 1 roof.

Figure 13. Post-test overall view of Test 2 roof.

Figure 14. Post-test close-up view of Test 2 roof.

Figure 15. Post-test overall view of Test 3 roof.

Figure 16. Post-test close-up view of Test 3 roof.

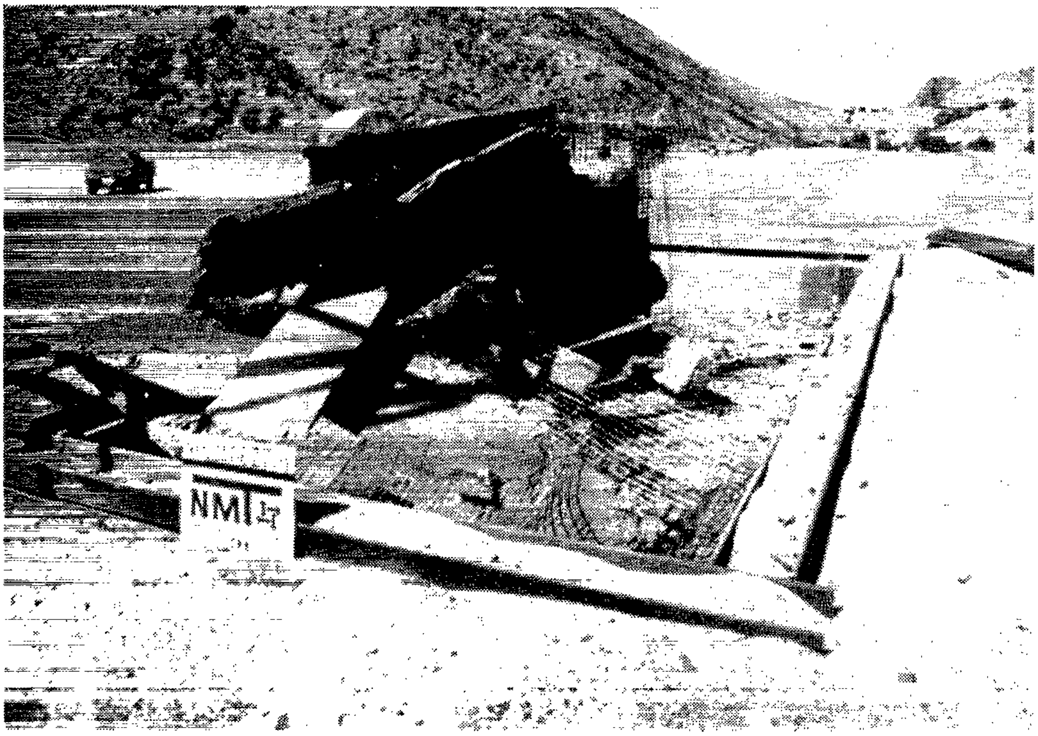

Figure 17. Post-test overall view of Test 4 roof.

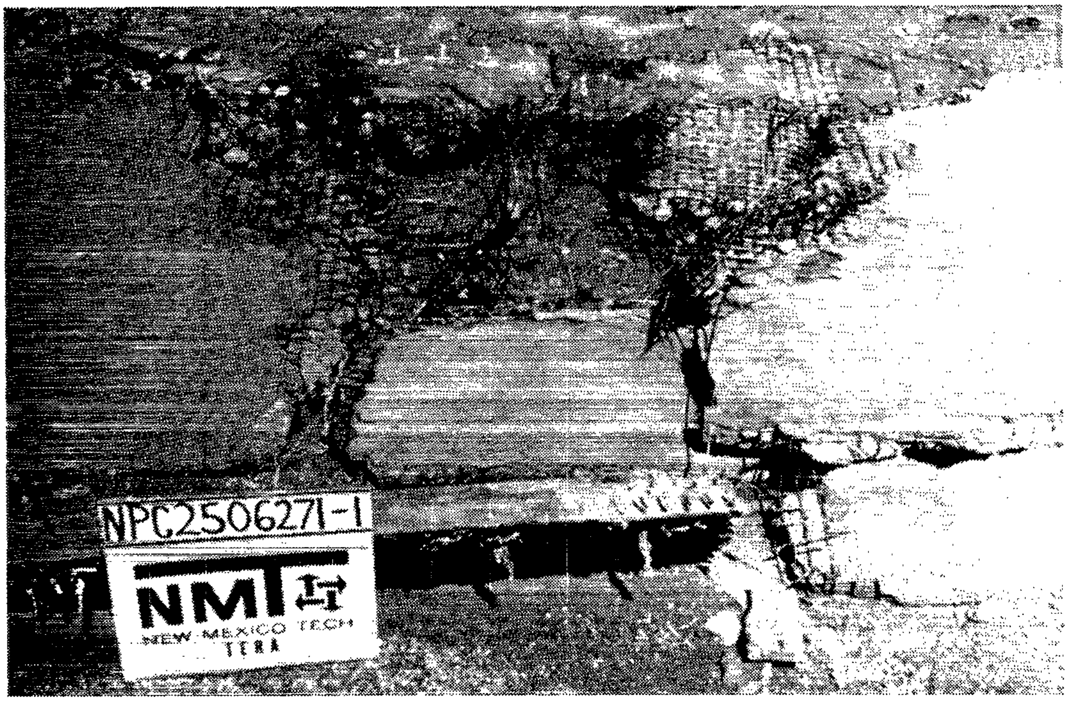

Figure 18. Post-test close-up view of Test 4 roof.

Figure 19. Post-test close-up view of Test 5 roof.

Figure 20. Post-test overall view of Test 6 roof.

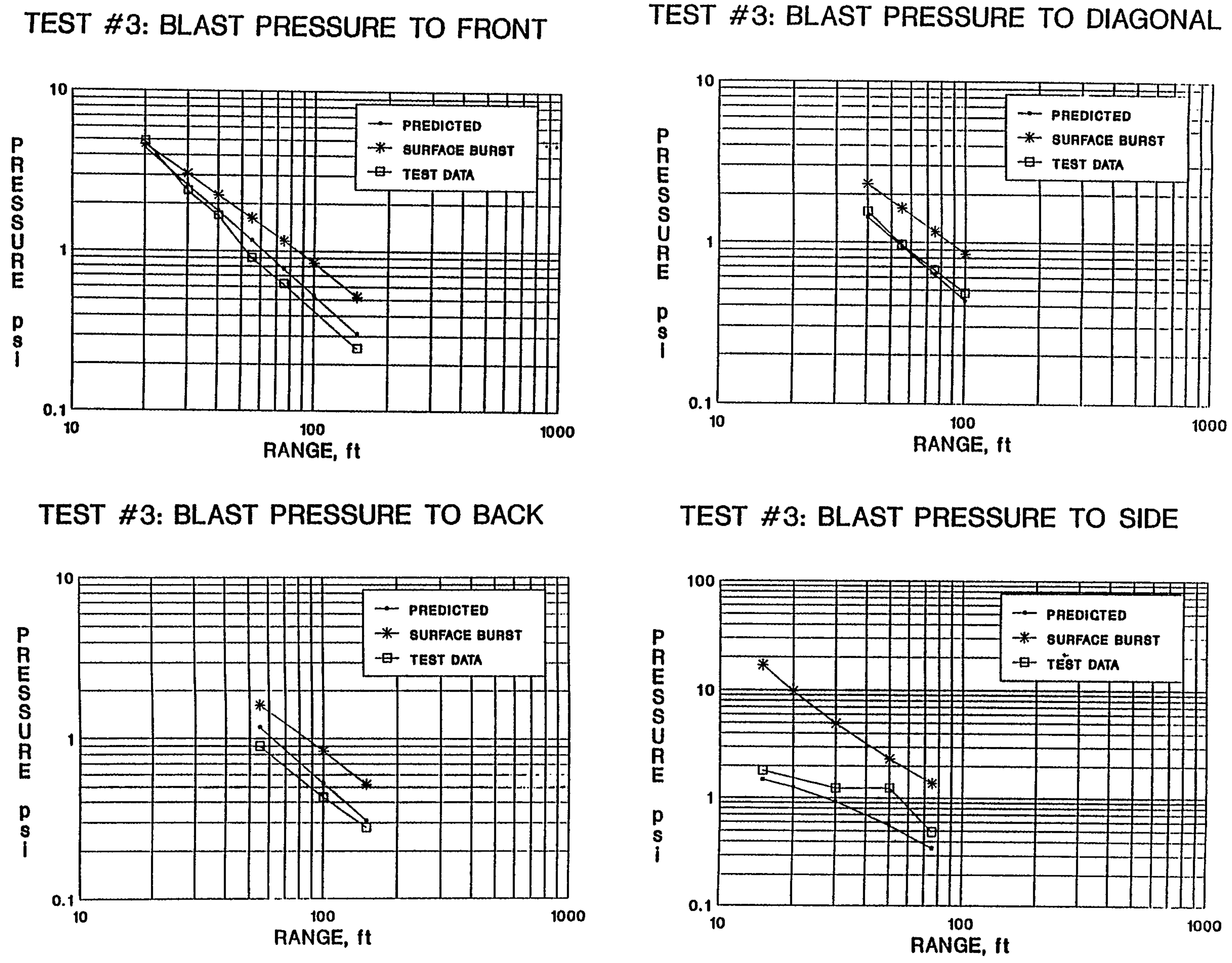

Figure 21. Peak pressure vs. range for Test 3.

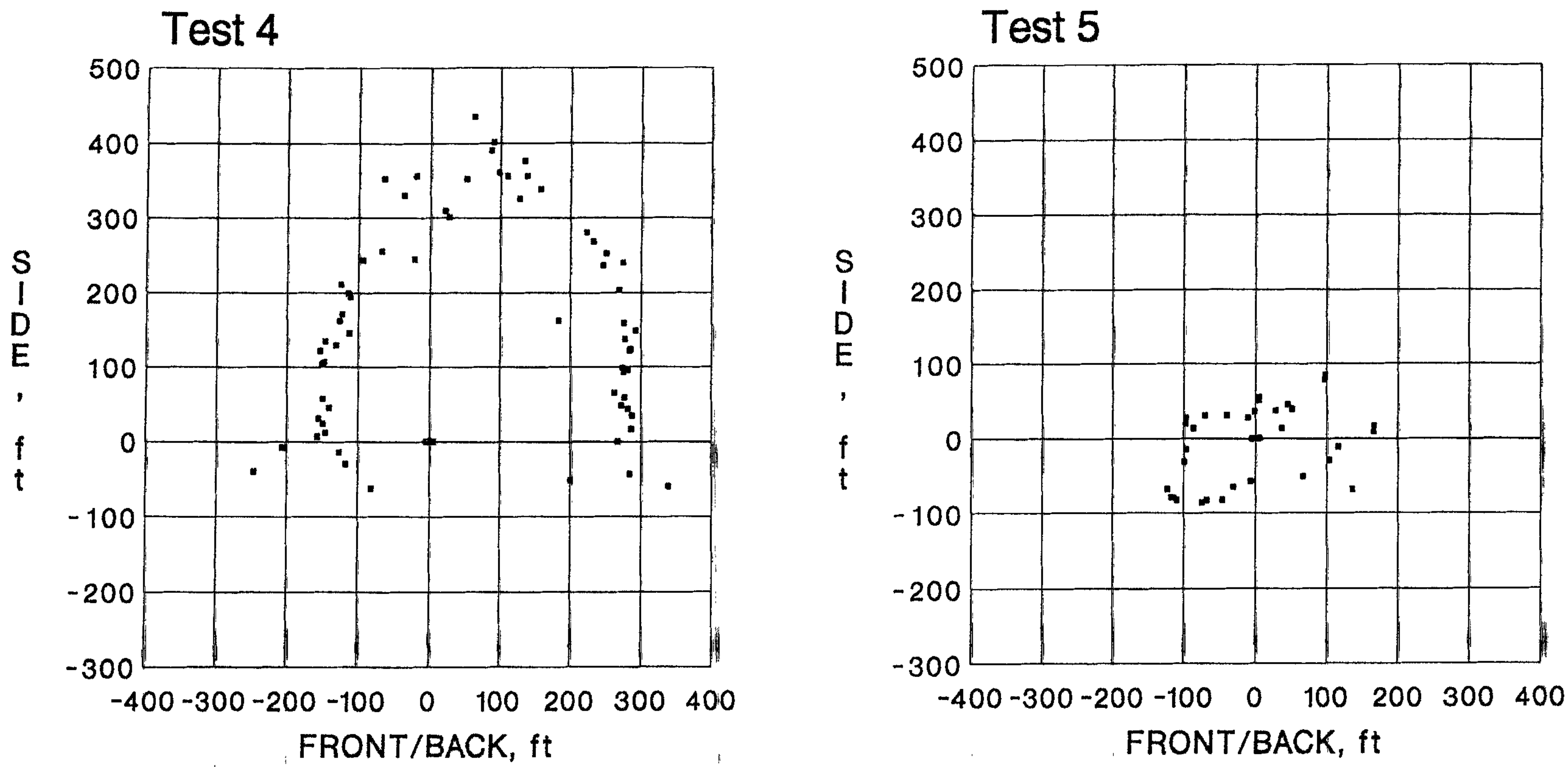

Figure 22. Location of debris collected outside recovery zones for Tests 4 & 5.

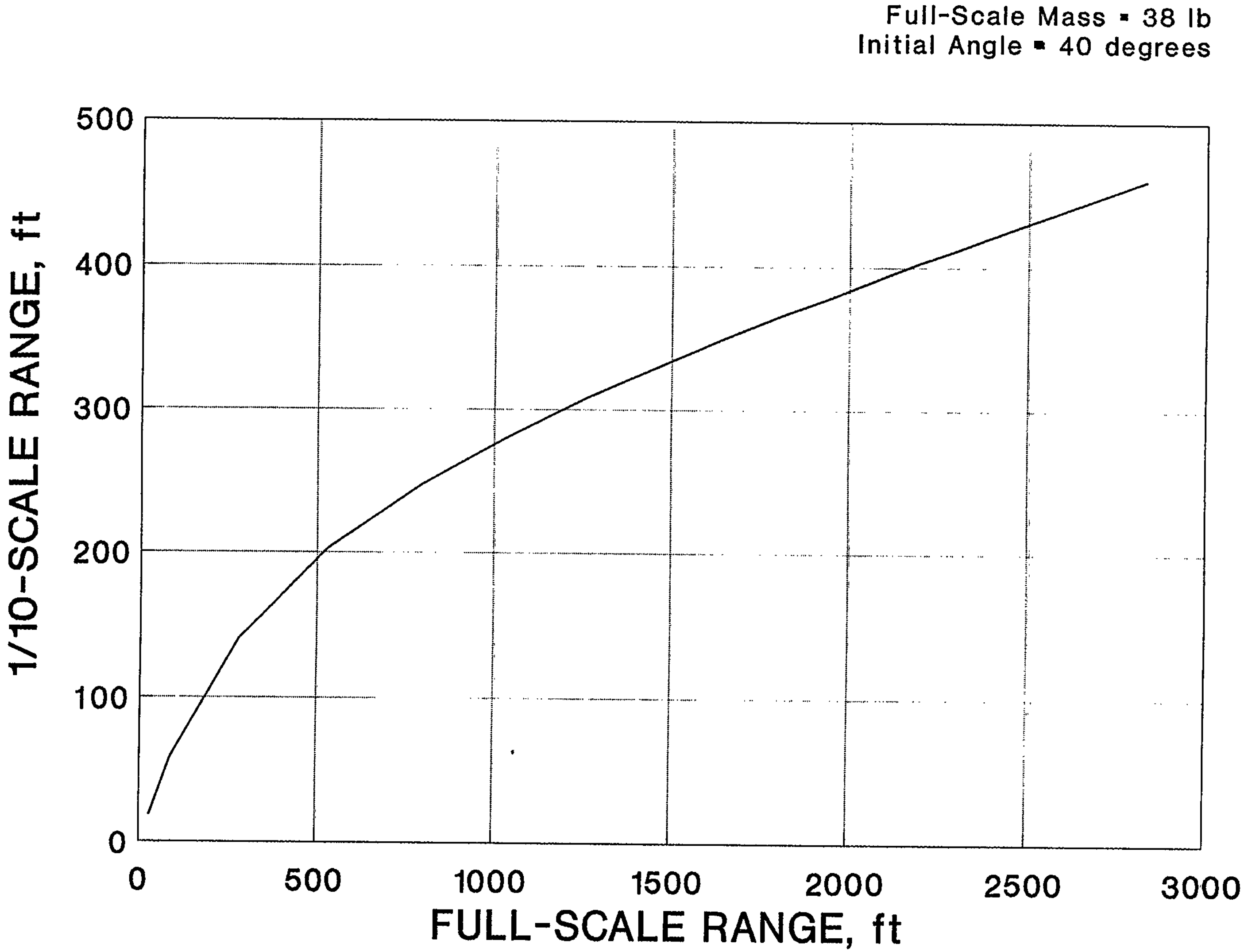

Figure 23. Full-scale vs. 1/10-scale debris distance relationship.

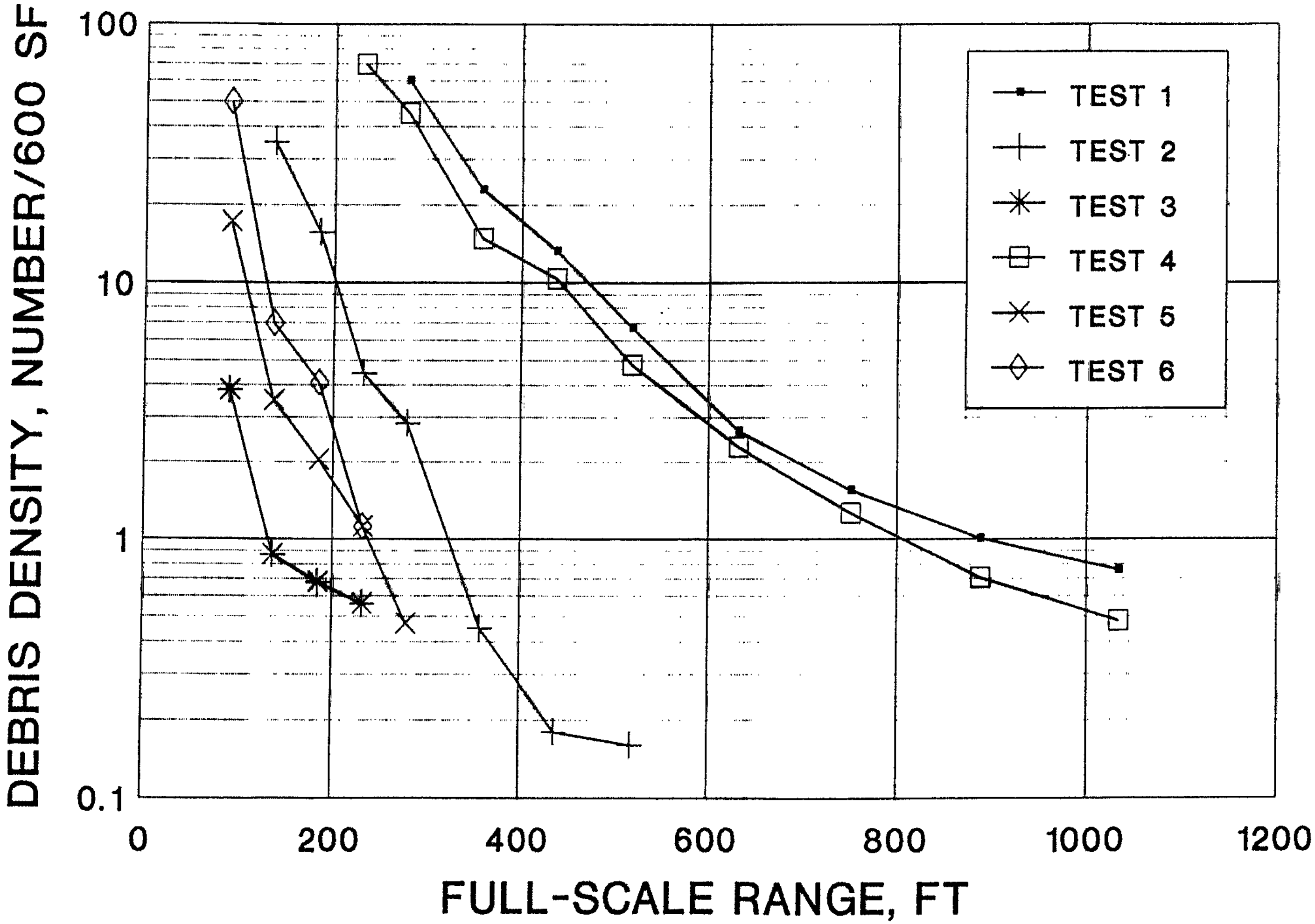

Figure 24. Debris areal number density distribution in side direction for Tests 1-6.

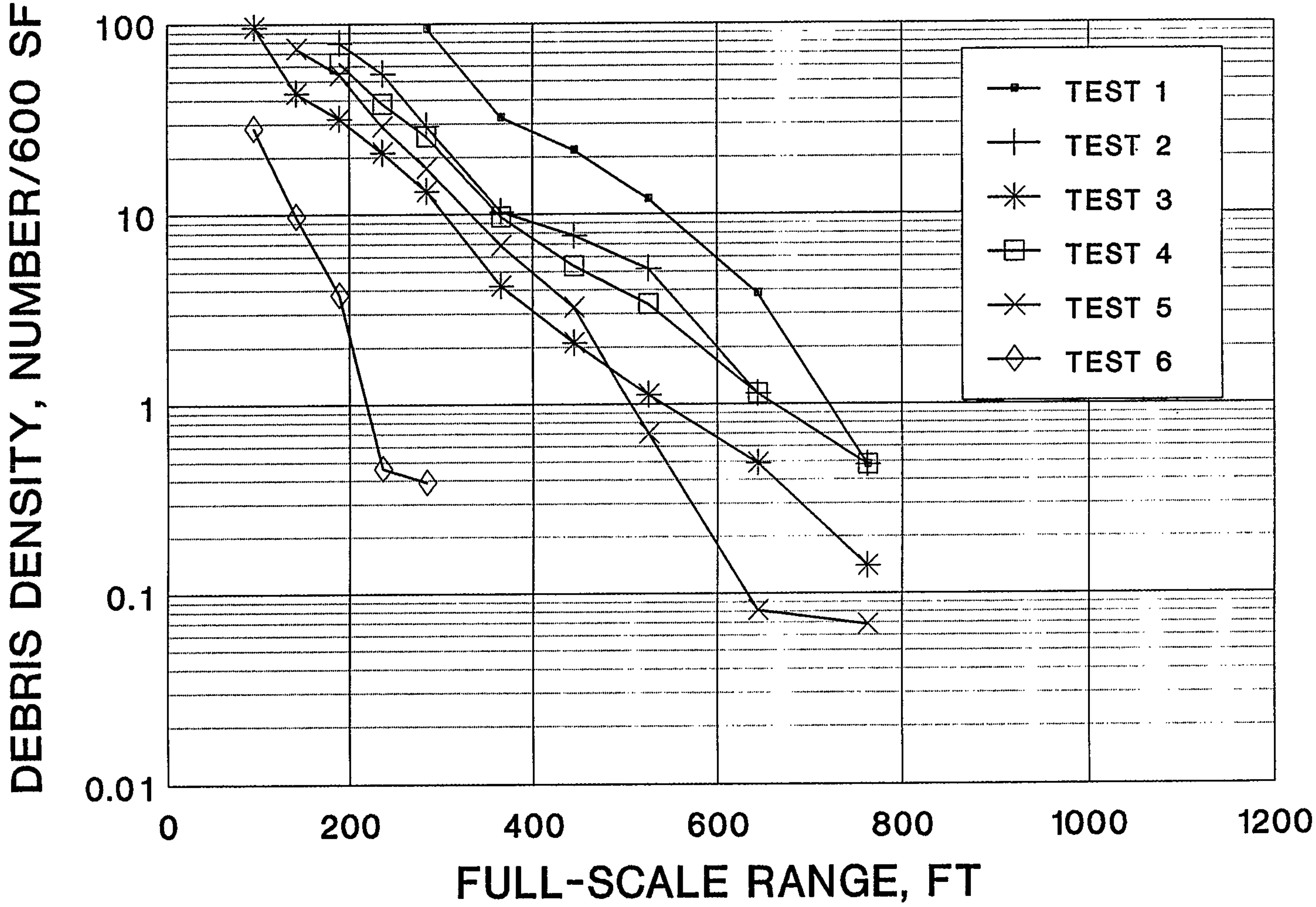

Figure 25. Debris areal number density distribution in front direction for Tests 1-6.

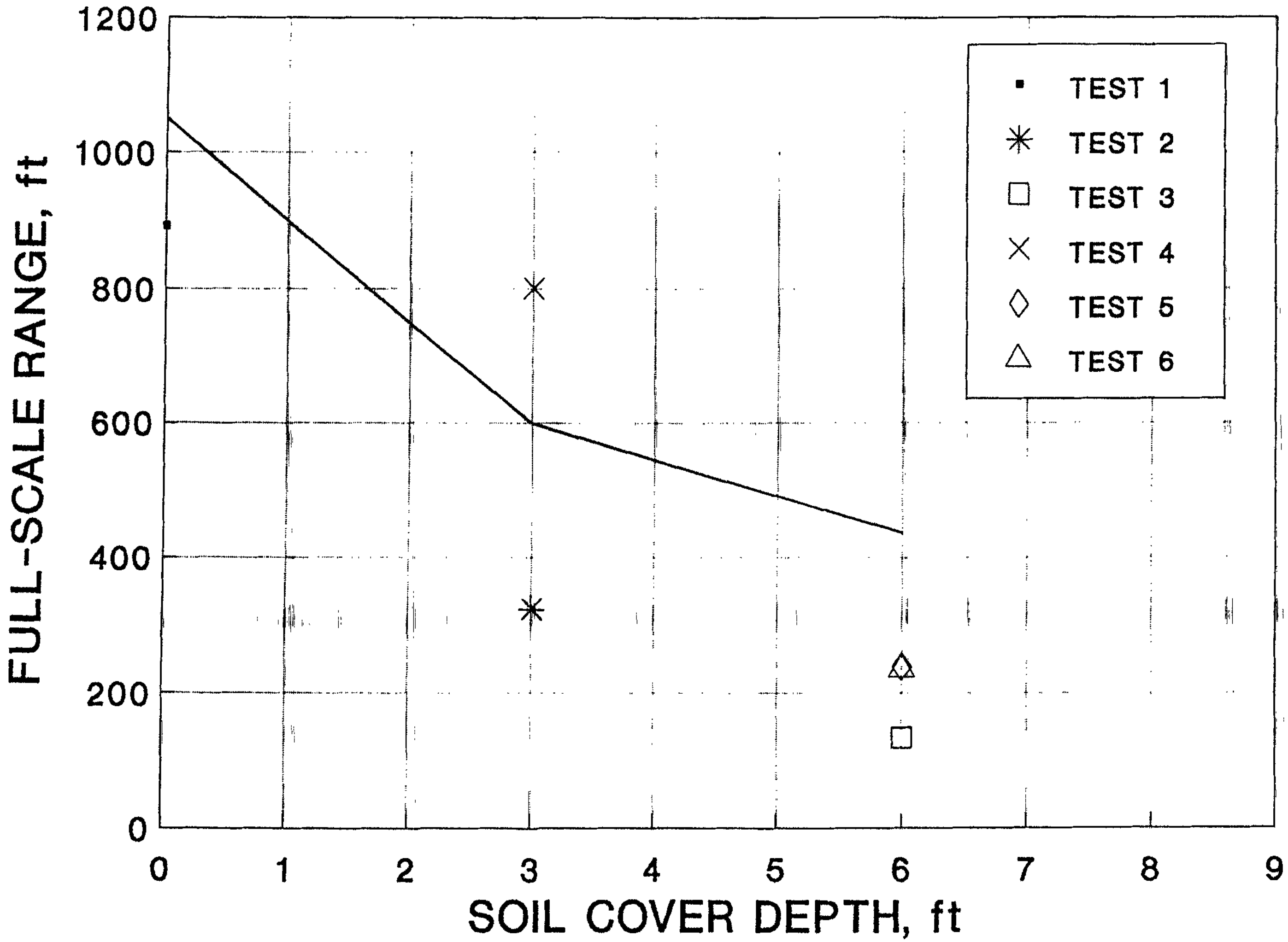

Figure 26. Measured vs. predicted full-scale safe debris range in side direction.

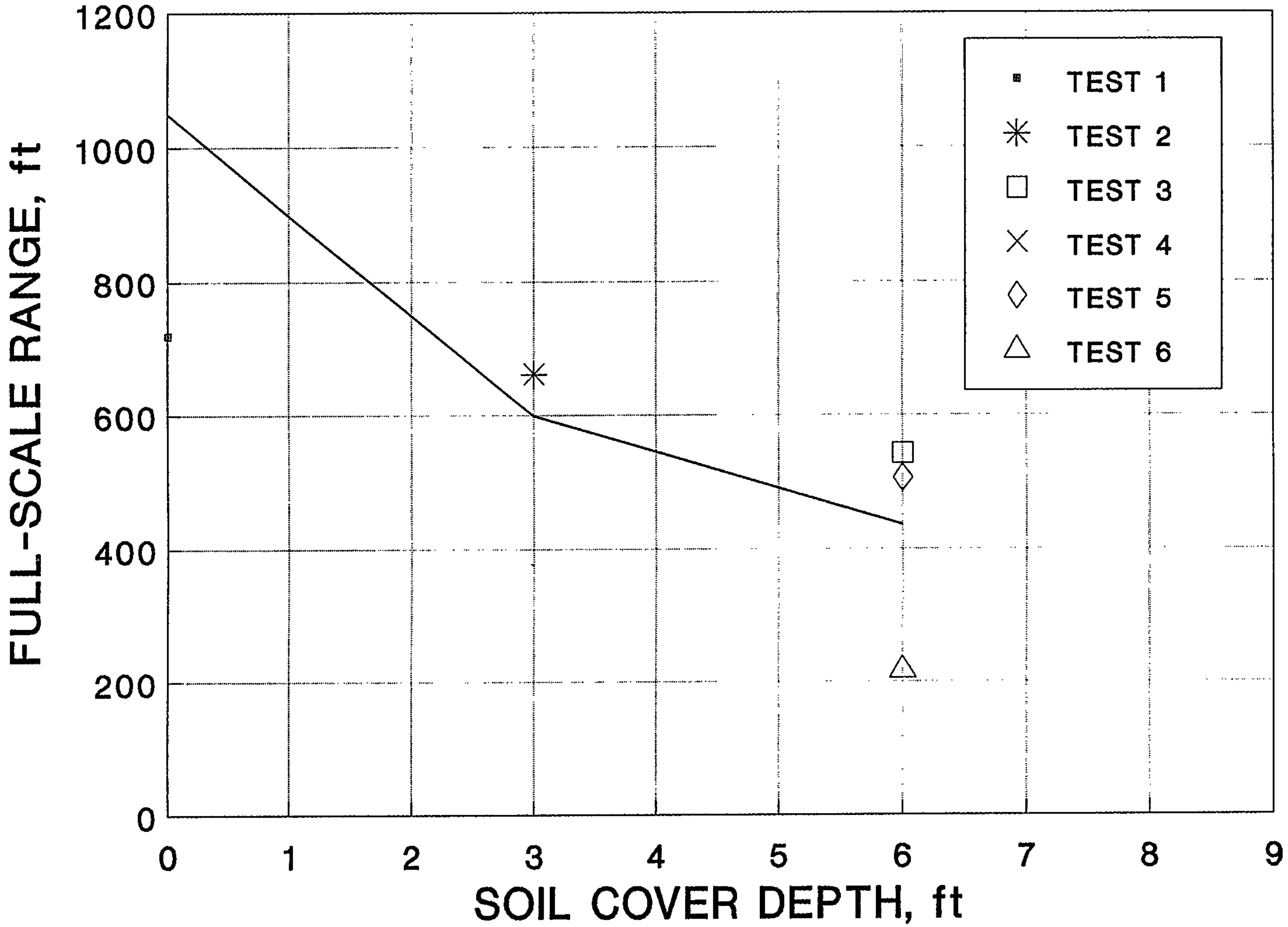

Figure 27. Measured vs. predicted full-scale safe debris range in front direction.